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THE S-66 LASER SATELLITE TRACKING EXPERIMENT

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THE S-66 LASER SATELLITE TRACKING EXPERIMENT

by Henry H. Plotkin

Introduction

Professor Coulomb, Professor Grivet, honored guests, ladies and gentlemen: I would first like to add my thanks to Professor Grivet, members of the arrangement committee of the 3rd International Conference on Quantum Electronics, and the European Preparatory Committee for Space Research for the very excellent arrangements which have been made on our behalf.

The optical tracking experiment initially planned by NASA for the S-66 satellite consists of illuminating a special satellite-borne reflector with a pulse from a laser and receiving the reflected light as seen in Figure 1. In this way we will measure the time-of-flight to determine accurate range and, if we have an angle sensor, obtain precise angle coordinates as well.

The S-66 satellite, without reflector, officially called the Polar Ionosphere Beacon had been planned for a long time as part of NASA's continuing program of atmospheric research. It thus has an existence independent of lasers and the uses discussed in this paper. Because of its non-zero drag and low mass to area ratio, it does not qualify as an ideal geodetic satellite. However, when the opportunity arose to add a reflector to this satellite without interfering with its primary mission, there seemed to be no reason not to get started as soon as possible. We would, at least, get a target into space, that would serve as a useful reflector for many years to come. Accurate optical tracking of S-66 would already be able to improve geodetic information to some extent and would lead to further improvements that could be used later in a probe specifically designed for relativistic experiments. Furthermore, it would be available for testing new pulsed optical transmitters and cw lasers as they developed. We could learn to cope with perhaps the most difficult of the problems confronting lasers in space: how to aim accurately and steadily at unseen moving targets in order to make effective use of the extremely high degree of collimation possible with lasers. I would not presume in an audience of this caliber to try to list experiments concerning effects of the entire atmosphere upon intensity fluctuations and coherence of optical beams which could be conducted. Indeed, this is the purpose of our presentation today: to inform those in the field of optics that such a reflector will soon be orbiting and then to allow the yeast of scientific interest and opportunity to ferment.

Description of the Satellite

The satellite itself, shown in Figure 2, will be described briefly. The pertinent parameters that would be important in laser experiments are repeated in the appendix. Distance across flats on the octagonal face is 18 inches and other dimensions are proportionally shown in the Figure. In its primary mission, a number of harmonically related tones will be radiated. By receiving these on the ground and comparing phases, one can derive a value for the integrated electron density over the radiation path. Since measurements of this sort will be carried out by about 60 international observers throughout the world, the project should result in a grand over-all profile of the earth's ionosphere: how it is affected by solar events and season.

Among the frequencies radiated is that of the NASA minitrack network. This should insure good orbital predictions throughout the active lifetime of S-66, or make it possible for an autotracking antenna to lock onto it. We notice that the top lid was free of external instruments and, therefore, fortunately available for our reflector.

Figure 3 illustrates that S-66 will travel approximately in a circular, almost polar orbit, with inclination 80°, at an altitude of about 1000 km. The satellite will be magnetically stabilized so that one end of its symmetry axis will always point in the magnetic north direction along the magnetic lines of force. It will very slowly rotate about this axis. An array of cube-corner reflectors placed on this face will generally find itself pointing toward the earth when the satellite is in the northern hemisphere. It is scheduled for launch during the spring of 1963.

Figure 4 shows the essential features of the reflector assembly in an artist's rendition. It was built by General Electric Missile and Space Division. It is composed of a mosaic of fuzed quartz cube-corners, each about 1 inch across the face. The triangle which ordinarily would form the front face of each prism has had its corners cut off to form a regular hexagon. The back surfaces are aluminized, epoxy cemented to aluminum brackets which, in turn are cemented to the aluminum honeycomb structure panels. The assembly weighs just 10 lbs., compared to the satellite's total weight of about 120 lbs.

Each of the cube-corners has the ideal property that light incident on it within its acceptance angle is reflected back in the direction from which it came. The specifications on the polishing of the reflecting surfaces were that 80% of the reflected light should actually fall back within a divergence cone with an angular diameter of 10^{-4} radians. This is only slightly larger than the diffraction cone due to a single reflector aperture.

Velocity Aberration Effect

In order to justify the use of a mosaic of small retro-reflectors instead of fewer but larger ones, let us briefly consider the velocity aberration effect demonstrated in Figure 5. If the corner reflector behaved properly, light entering along the solid line would be reflected back to its source along the solid line. However, S-66 will be moving at a velocity of about 7.4 km/sec. It will, therefore, transform the direction of the incoming ray into its own reference frame, consider the ray incident along the dotted line and reflect back along the dotted line. When we transform back again to a stationary earth, we find that the ray has been deflected by an angle as great as 2 v/c.

The geometry of our experiment is such that the displacement of the reflected beam on the ground can be as much as 70 meters. If the spot were small, such as would result from a large, high-quality cube-corner, we would be required to displace the transmitter and receiver according to the velocity and direction expected for each pass. Moreover, the displacement would be changing within a pass. This would have been a serious operational burden, and we had to resign ourselves to sacrifice reflected intensity for convenience in this first experiment. With the present arrangement, the transmitter always lies within the reflector's divergence cone, so we can put the receiver on the same mount.

Plans for Early Transmitter

As a basis for some specific numerical calculations, the pulsed ruby laser NASA will use in its experiments during S-66's early life will be described very briefly. Figure 6 is a schematic of the Q-switched laser with which we have been conducting field experiments. There are no really novel features: ruby rod 3/8" x 6", total internal reflection roof prism rotating at 12,000 rpm as a Q-switch, collimating optics, and boresighting optics. The beam divergence can be controlled down to 10^{-3} radians angular diameter. Figure 7 is an exploded view of the laser without collimating optics. Using air cooling at dry ice temperatures, we have been able to operate at one pulse per second indefinitely. Each pulse has an energy of somewhat less than 1 joule, and a duration of about 0.2 microsecond. We find that the timing of the flash within a rotation cycle of the prism is extremely critical in avoiding multiple pulses, but that once the maser has been adjusted and warmed up, it is stable.

Numerical Estimate

Figure 8 will help give us an idea of signals we might expect in a typical situation. In this case we are assuming that a pulse of 1 joule from a ruby laser, which is diverging in a cone of 10^{-3} radians, attenuated to 0.8 in each passage through the atmosphere, is reflected by the array having an effective area of 200 cm^2, at a range of 1500 km, the reflected rays contained uniformly within a cone of 10^{-4} radian diameter, and received in a telescope with aperture area of about 500 cm^2. This is only a modest 10-inch telescope. The number of photons collected is not inconsiderable.

What can we do with these? If these were focused to an image of 30 micron diameter on sensitive astrographic film we would just begin to get photographic impressions. Of course, we need not Q-switch a laser for photography, and so we can gain an order of magnitude in intensity by running the laser in a normal fashion. Thus, one could obtain precise photographs of S-66 in relation to the fixed stars on a wide field astronomical plate.

As for photoelectric ranging, one would, of course, use a narrow filter about the ruby wavelength in order to discriminate against background. With a 10 Å filter, a 0.2 microsecond pulse duration, and the parameters quoted above, we would expect a post-detection signal-to-noise of better than 10 to 1 against a clear daylight sky. (The detection time constant would be made to match the pulse duration for optimum signal to noise.)

Early Receiver Plans

Again, in order to make our discussion specific, the equipment we are prepared to use shortly after S-66 is launched will be described. Figure 9 is the mount for a 9558 photomultiplier tube, with provisions for up to 3 interference filters, and reflex optics for boresighting. The iris which allows us to adjust the field of view is placed in the focal plane of the telescope shown in Figure 10. It happens to be a tracking telescope which was available at the Wallops Test Station at which some NASA test rockets are launched. The detector in the previous Figure merely slips into the fittings that ordinarily hold the recording camera. The laser is mounted under the instrument and carefully boresighted to it.

During operation, we would have a prediction as to when and where the satellite is expected to be as it comes over the horizon, accurate, perhaps, to $\pm$ 1/4 degree. Two operators, one for azimuth, one for elevation, look through viewing scopes and detect it in their viewing field illuminated by the sun against the dark sky (We expect it to be equivalent to an apparent 8th magnitude star.). They then track to keep S-66 at the center of their fields. This tracking can be good to 1 or 2 minutes of arc.

We track across the sky in this way, taking range data, if we want, once per second, using the range display equipment shown in Figure 11. This is nothing but a very elementary radar setup. An optical signal from the transmitted beam starts a counter operating at 100 mc/s and the reflected pulse then stops the counter. The time printed out will thus have a resolution of $\pm 10^{-8}$ sec. or $\pm$ 1 1/2 meters in range.

This arrangement is certainly not satisfactory. Although we have intrinsically an optical tracking system which should be suitable during the day or in the shadow of the earth, we have again limited ourselves, as before, to the twilight condition: sunlit satellite and dark sky.

Real-time Automatic Digital Optical Tracker

In order to be able to acquire the satellite within the narrow laser beam over a full 24 hours, we are developing an instrument of the type shown in Figure 12. As before, the laser is mounted on a tracking telescope. Now, the sensor is a sensitive image orthicon. The information gathered by the sensor is stored in a digital computer. By sensing the deviation of the target from the optical line of sight, a servo error signal is generated to drive the telescope accurately on the target. The angle readout from shaft angle encoders is expected to be accurate to 5 seconds of arc under the accelerations expected from satellites.

In preparation for a satellite pass, the telescope will begin to drive along a predicted trajectory program inserted into the computer. When the target is acquired, error signals will correct the predicted orbit and achieve lock-on. Our chances for successful acquisition will then depend upon the accuracy of the orbit generated from previous radio and optical tracking data. We are hopeful, because of the excellent tracking now being accomplished, that we will be able to point blindly at S-66, well within the 1 milliradian transmitter beamwidth.

In Figure 13, is shown the optical system of "Radot" as it is now being developed. The light may take either of 2 paths, giving a choice of wide or narrow fields of view, or a mirror may be inserted for direct viewing by the operator.

In Figure 14, we get an idea of what the entire instrument will look like. The mount and drive must be rigid, accurate, and smooth beyond any telescope yet built. We chose a horizontal mount rather than an astronomical siderial mount, because it is more convenient for tracking satellites. It is being built by Consolidated Systems Corporation.

Conclusion

I have thus described to you a reflector that will soon be orbiting, and briefly shown you some of our plans connected with it. Our aim is to explore the many questions that must be answered before lasers become useful in space. The answers will have scientific interest to the men in this audience, and they will certainly be valuable to NASA.

FIGURE 1

LASER SATELLITE TRACKING EXPERIMENT

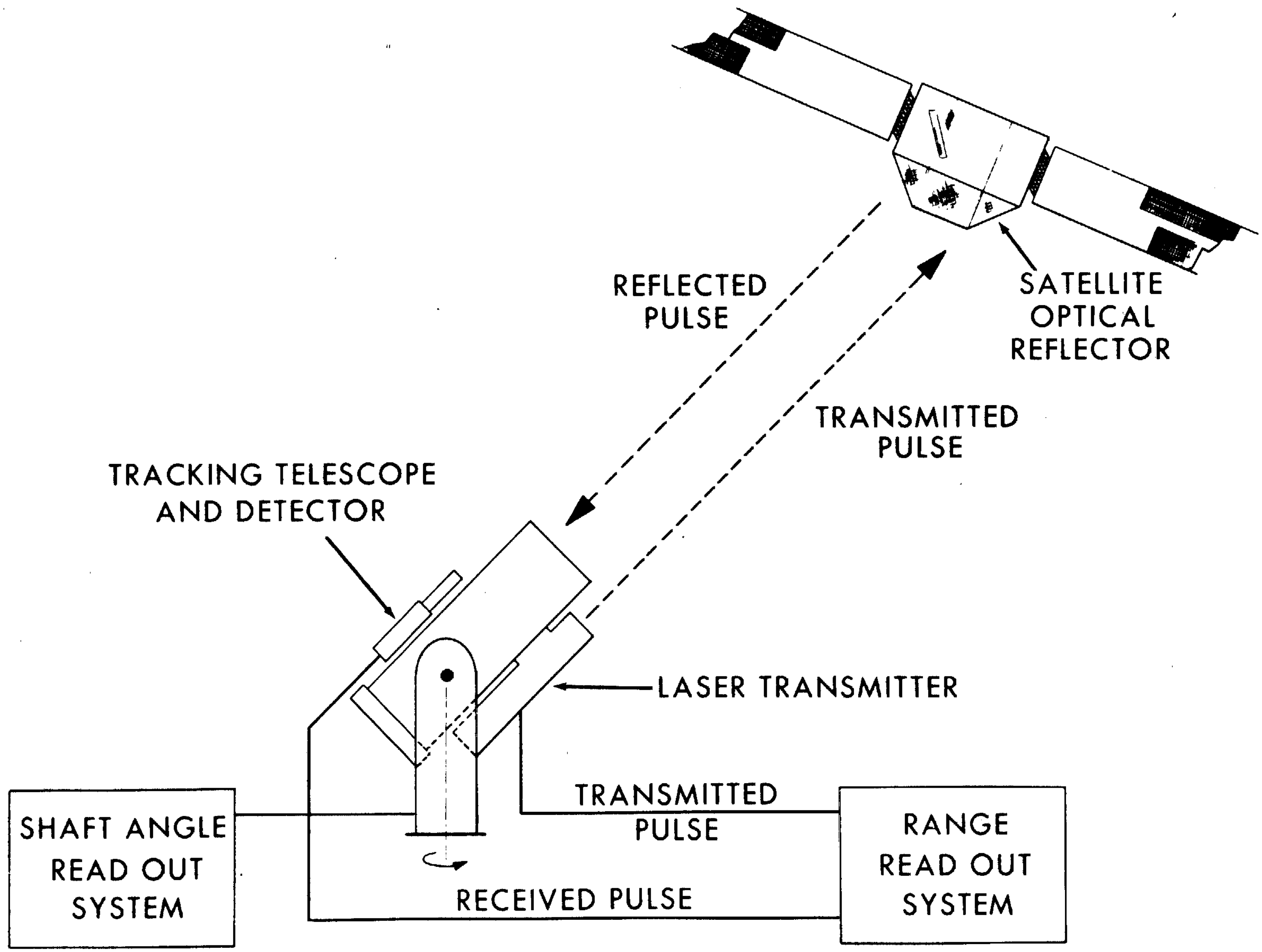


FIGURE 2

S-66 SPACECRAFT, CUTAWAY VIEW

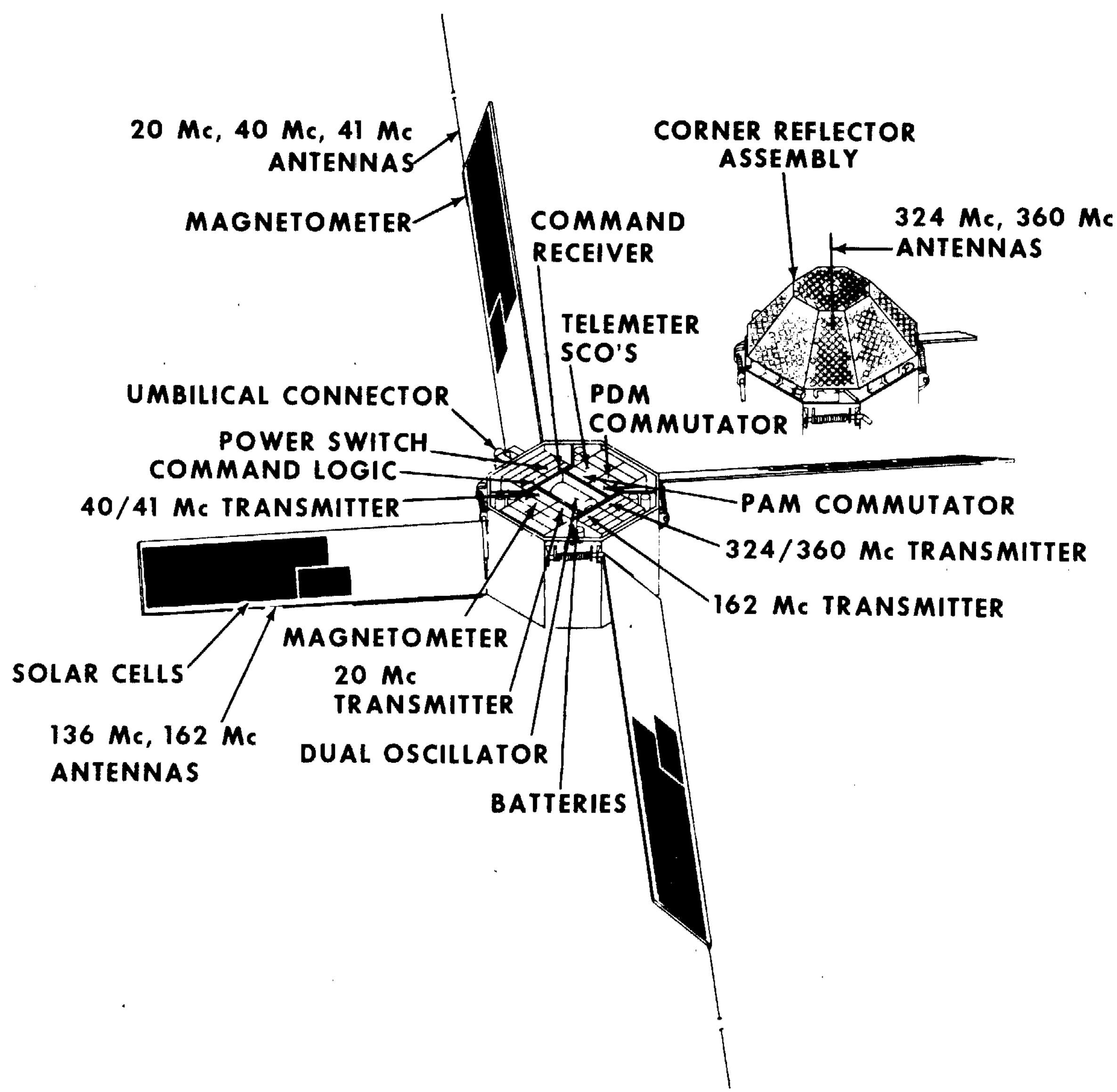


FIGURE 3

S-66 ORBIT AND STABILIZATION

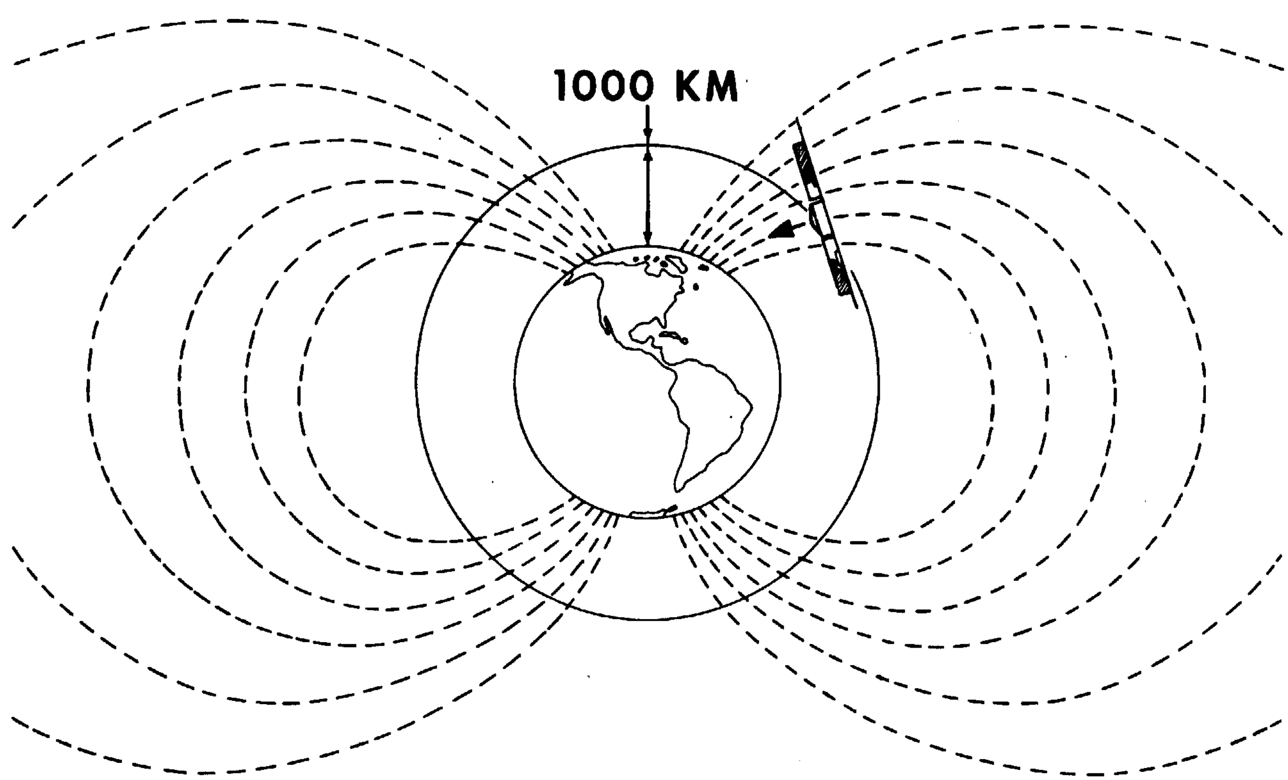
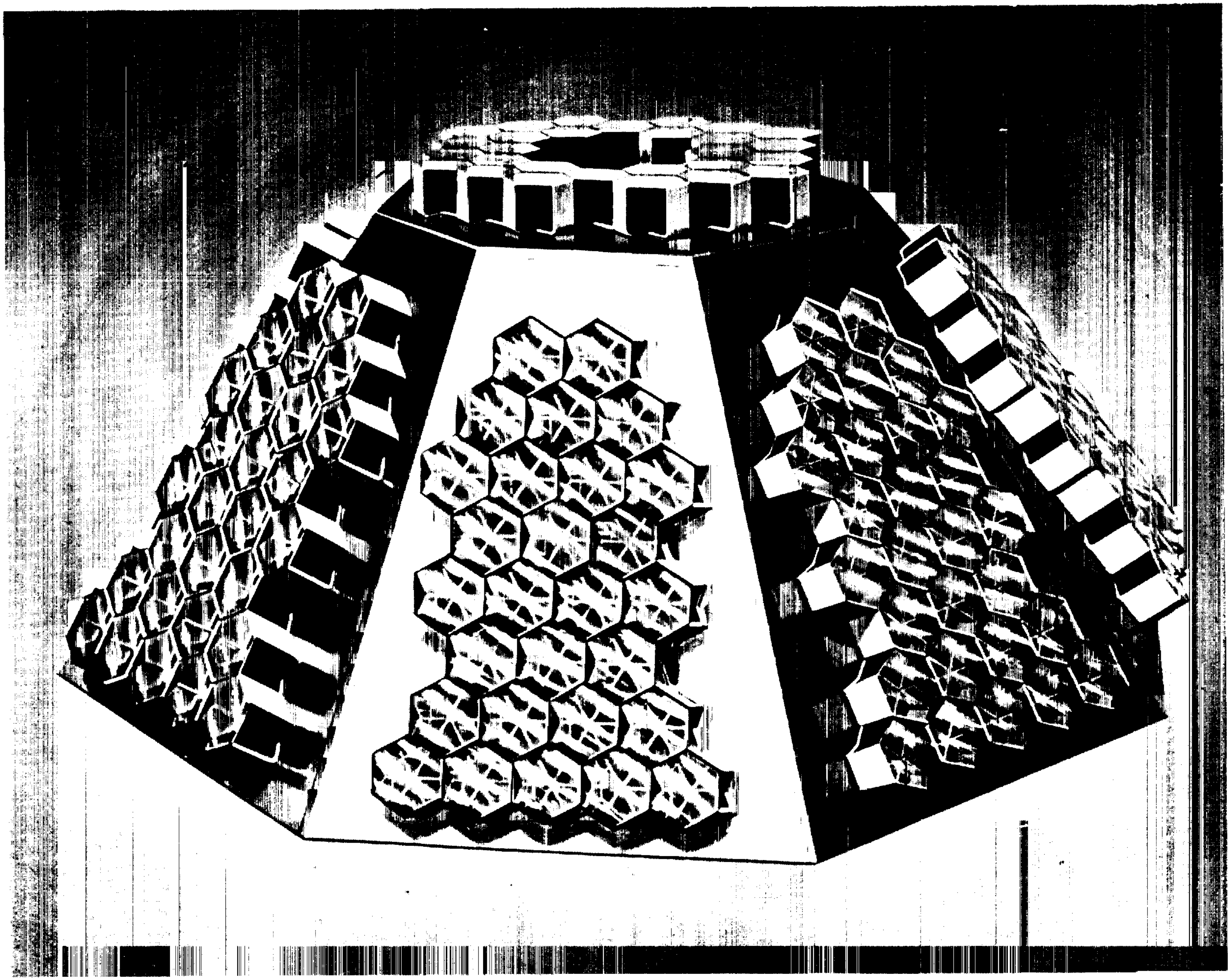
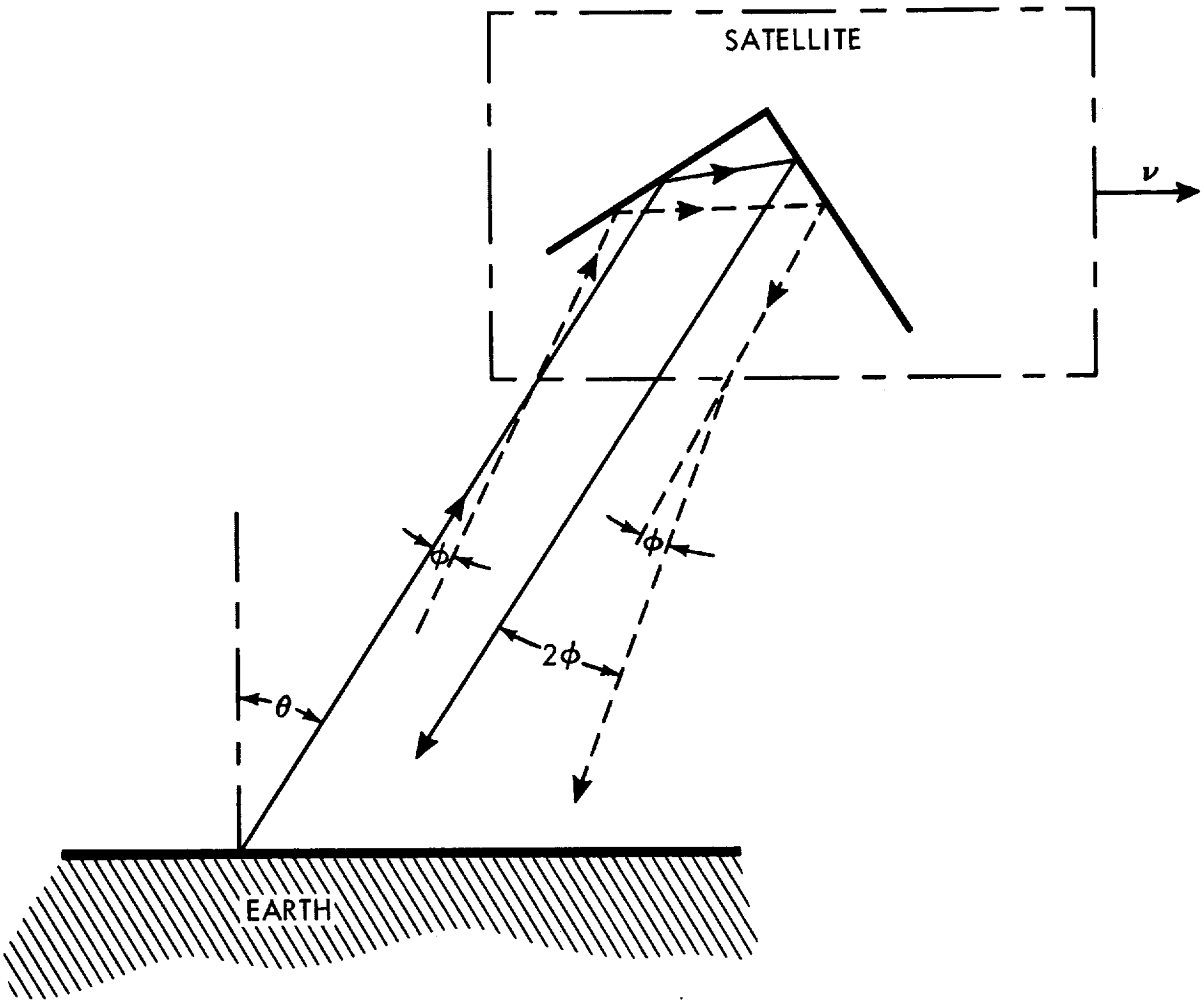


FIGURE 4





$$2\phi = \theta - \tan^{-1}\left[\frac{c \sin \theta - 2\nu}{c \cos \theta}\right]$$

Figure 5. Non-Relativistic Velocity Aberration

FIGURE 6

SCHEMATIC REPRESENTATION OF LASER TRANSMITTER

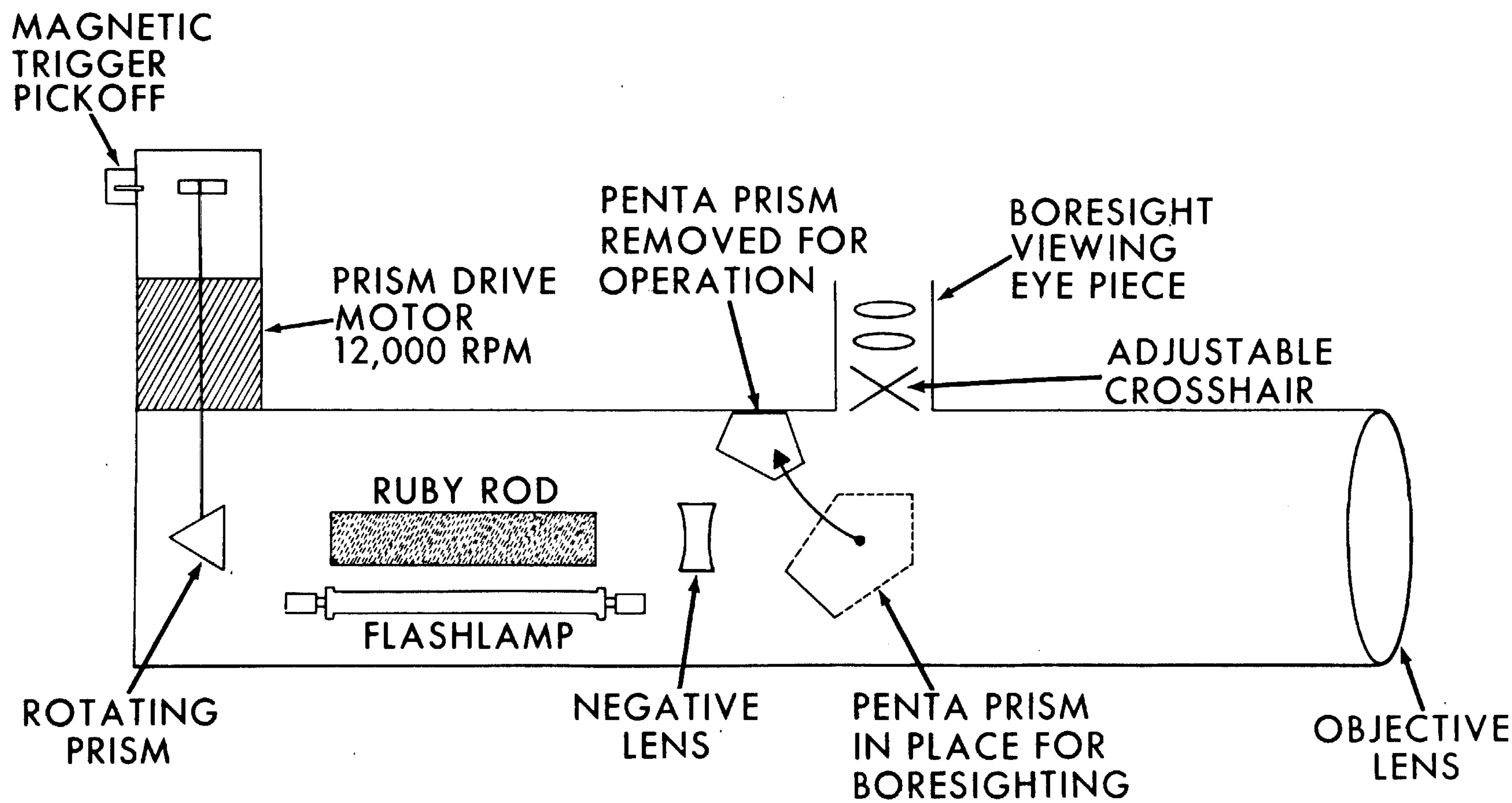


FIGURE 7

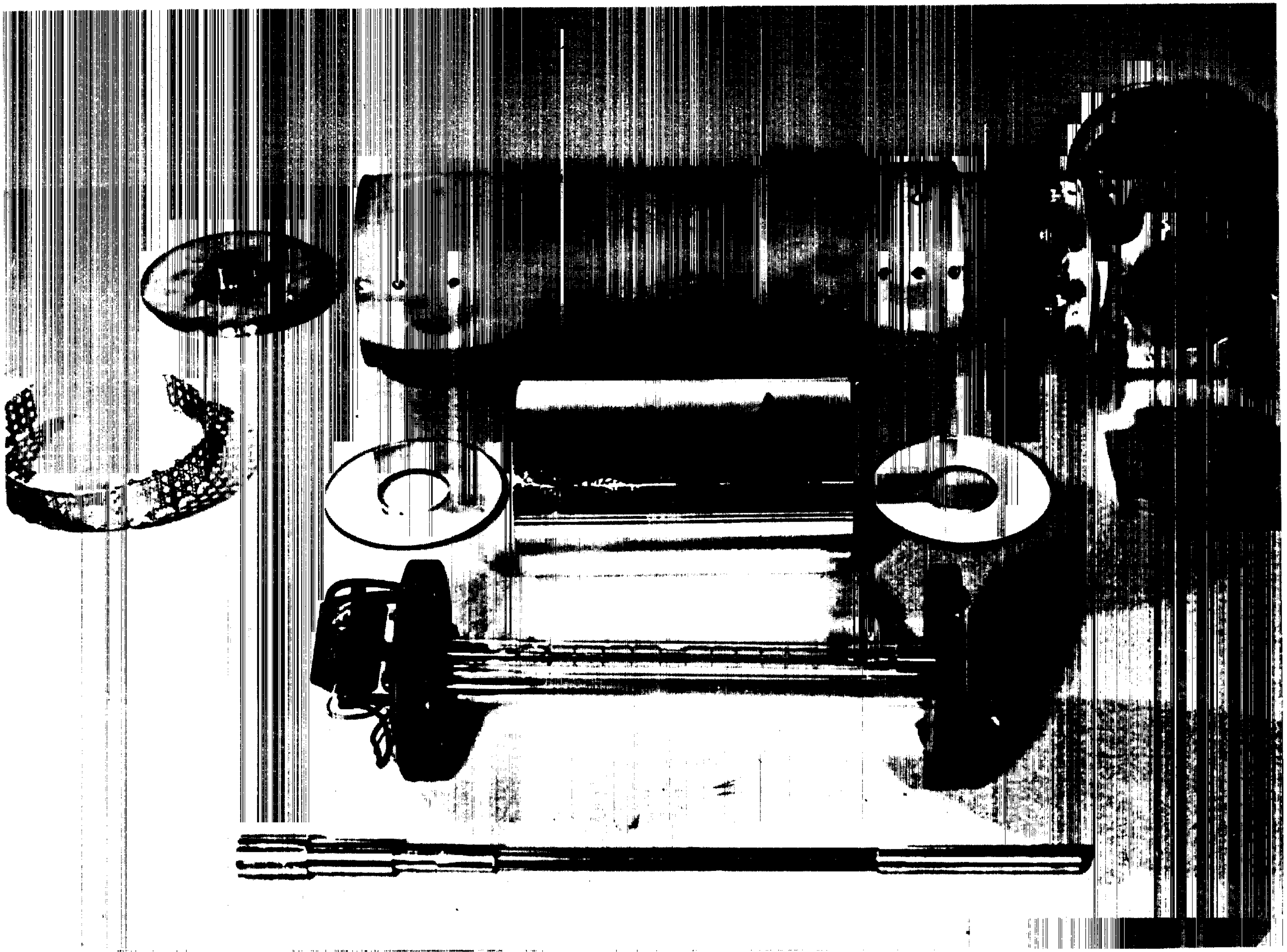


FIGURE 8

NUMBER OF PHOTONS ENTERING TELESCOPE:

$$N = \frac{16\, E\, \lambda\, \Delta^2\, \alpha\, A_S\, A_R}{\pi^2\, h\, c\, \theta_t^2\, \theta_S^2\, R^4} = 3.62 \times 10^4 \text{ PHOTONS}$$

ASSUMED PARAMETERS

E = TOTAL PULSE ENERGY = 1 JOULE

λ = RUBY LASER WAVELENGTH = 6943Å

Δ = ONE-WAY ATMOSPHERE TRANSMISSION = 0.8

α = REFLECTOR EFFICIENCY = 0.5

A_S = REFLECTOR PROJECTED AREA = 200 cm^2

A_R = TELESCOPE APERTURE AREA = 506 cm^2

θ_t = TRANSMITTER DIVERGENCE = 10^{-3} radian

θ_S = REFLECTOR BEAM DIVERGENCE = 10^{-4} radian

R = RANGE = 1500 km

FIGURE 9

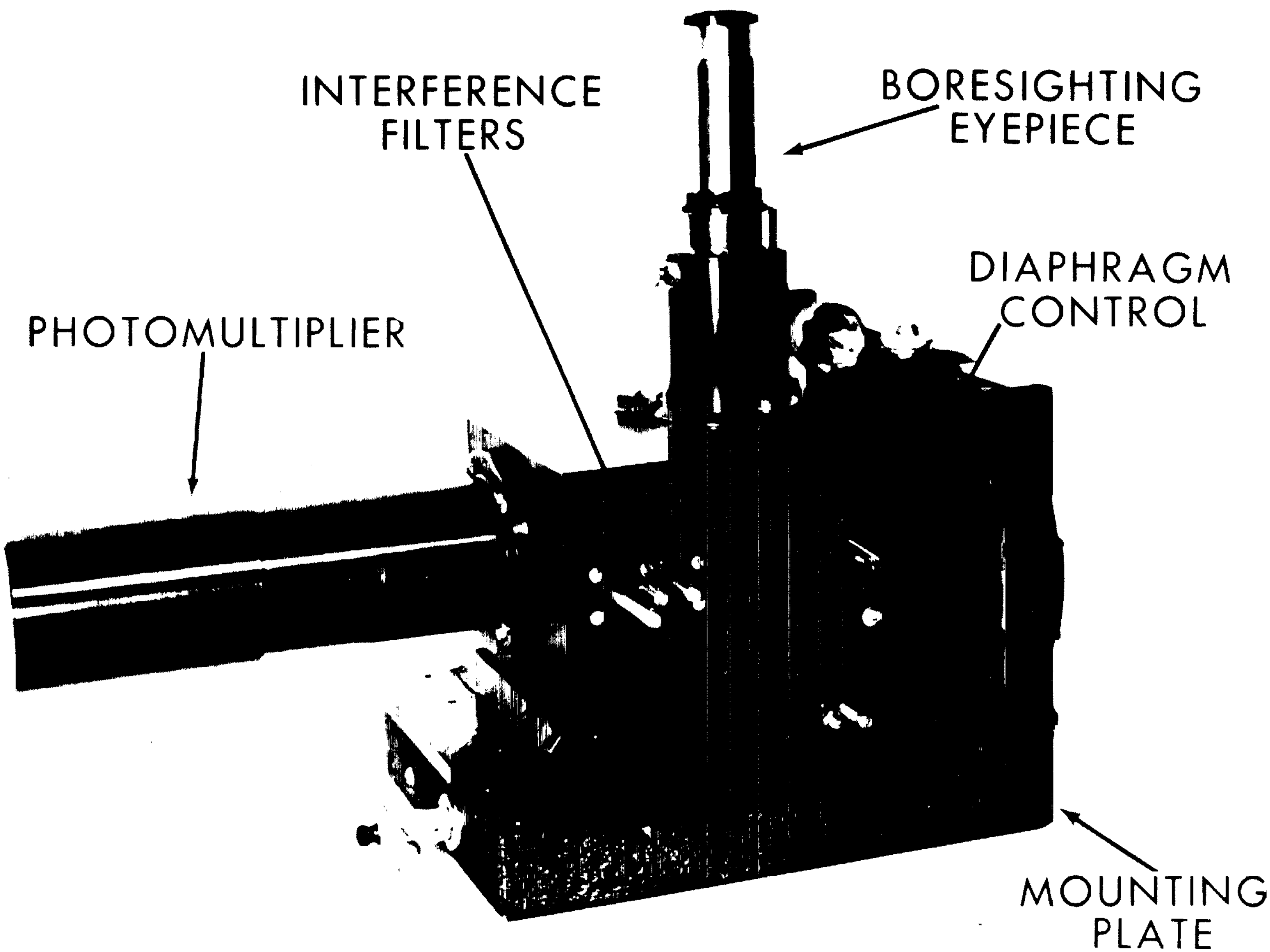

INTERFERENCE FILTERS
BORESIGHTING EYEPIECE
DIAPHRAGM CONTROL
PHOTOMULTIPLIER
MOUNTING PLATE

FIGURE 10

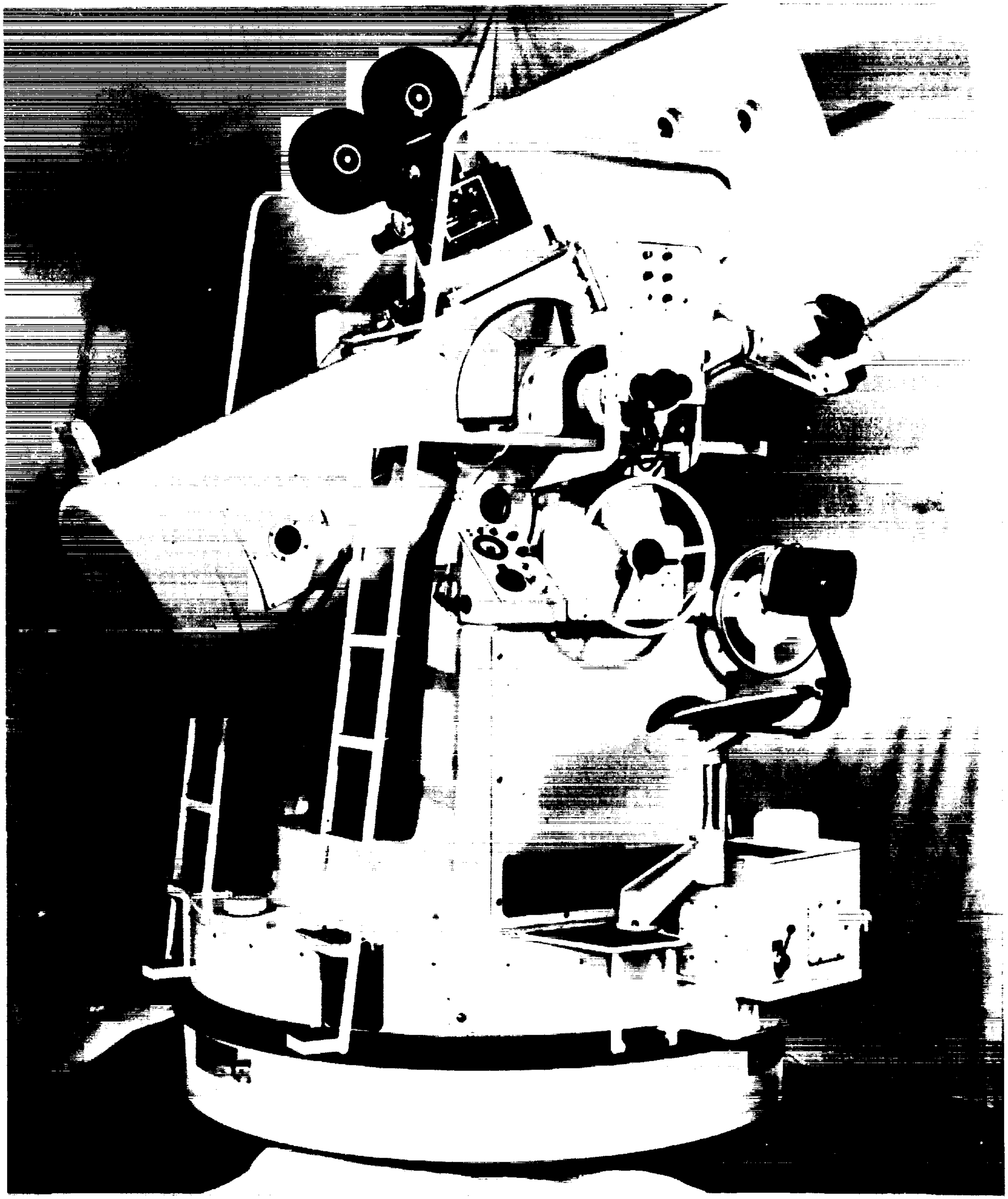


FIGURE 1-1
IGOR MARK III

FIGURE 11

DIGITAL RANGE READOUT SYSTEM

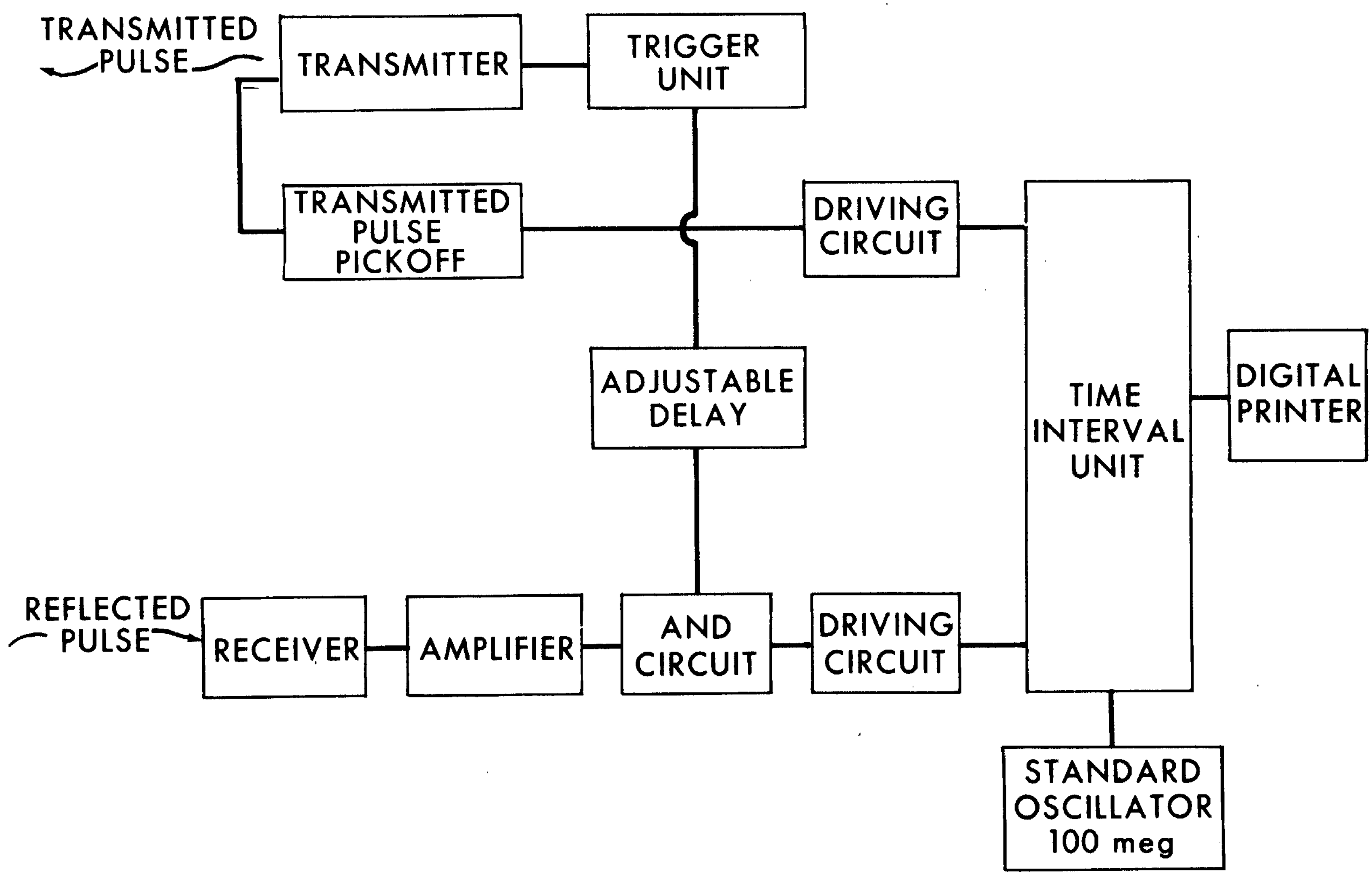


FIGURE 12

REALTIME AUTOMATIC DIGITAL OPTICAL TRACKER

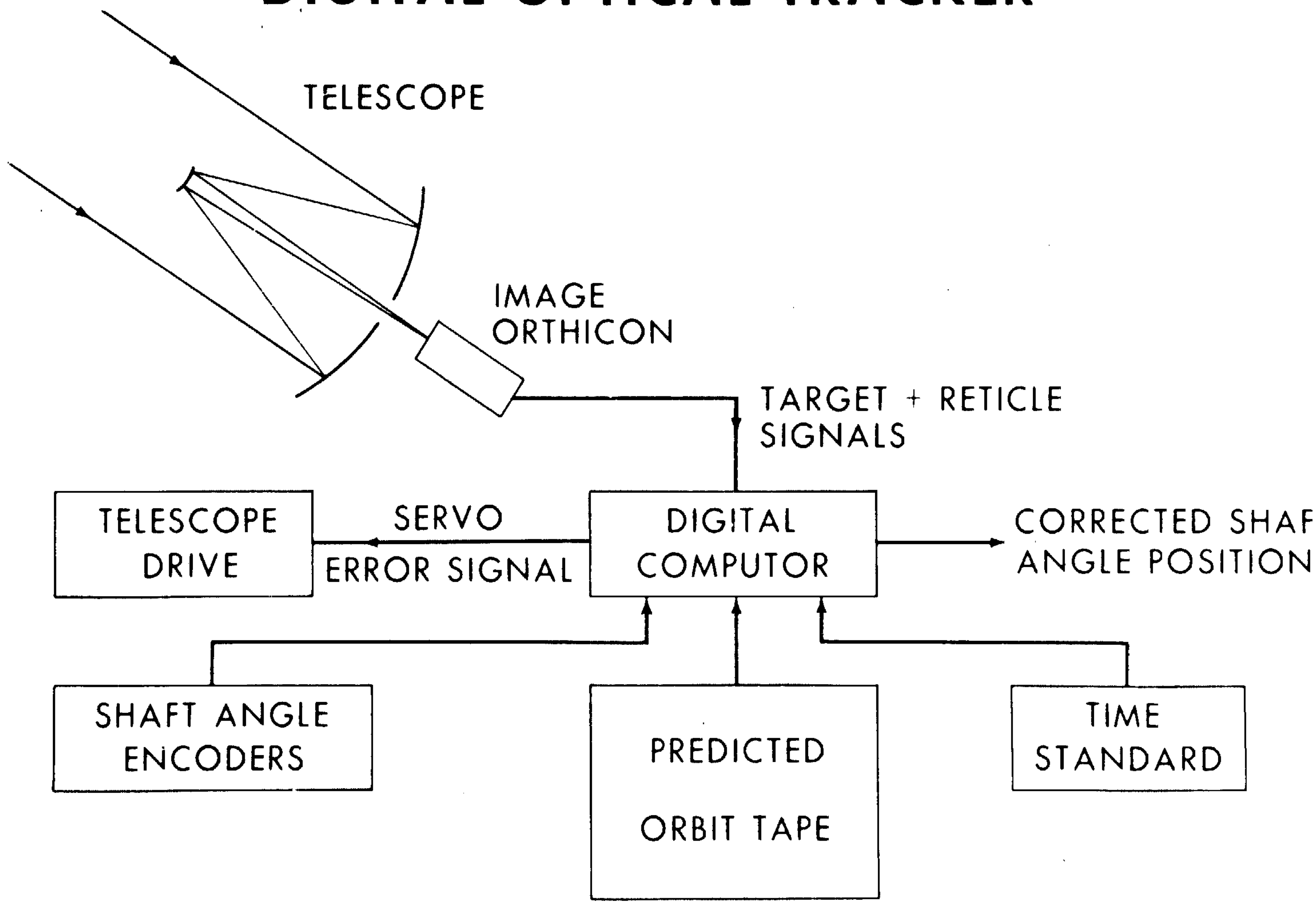


FIGURE 13

RADOT OPTICAL SYSTEM

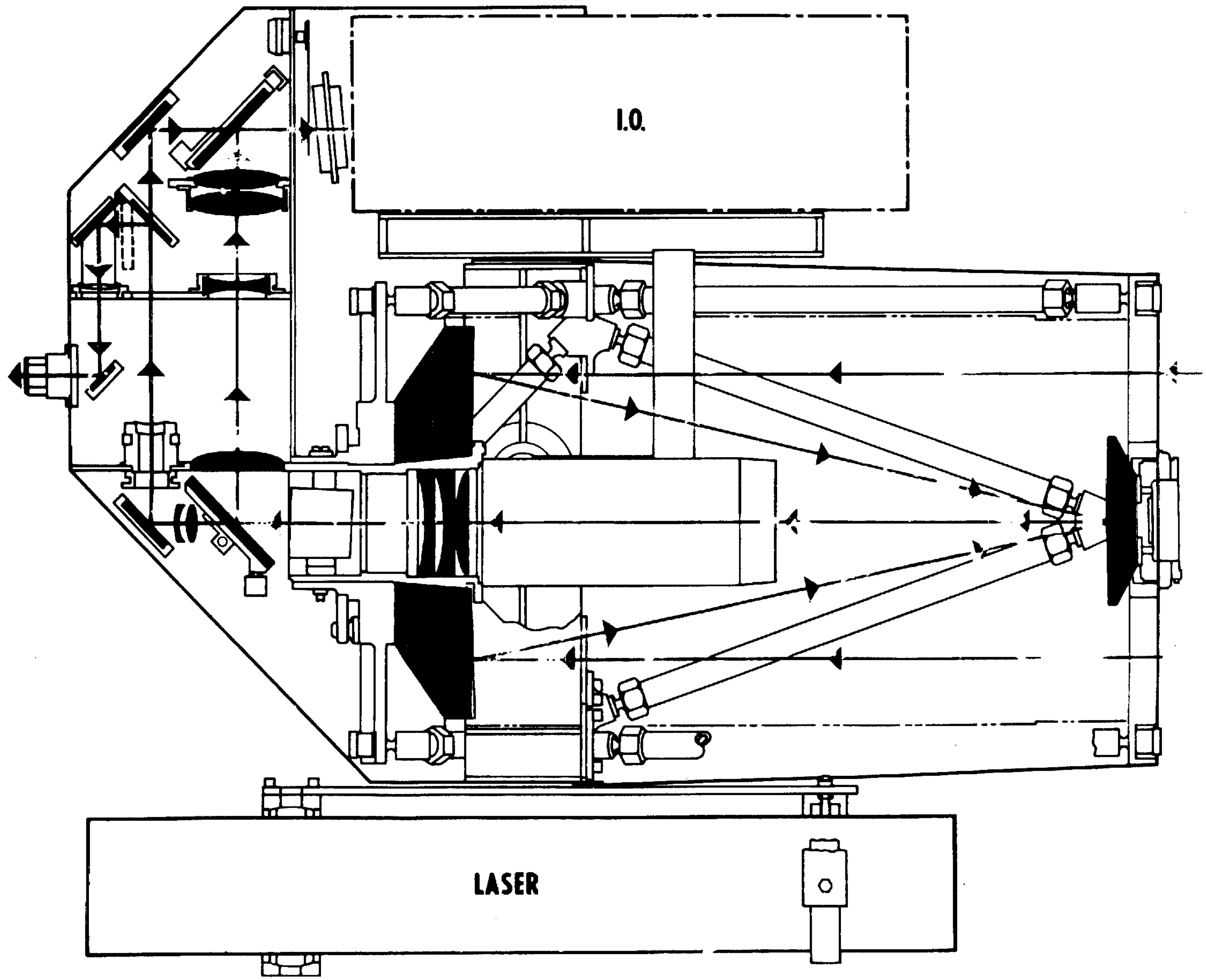
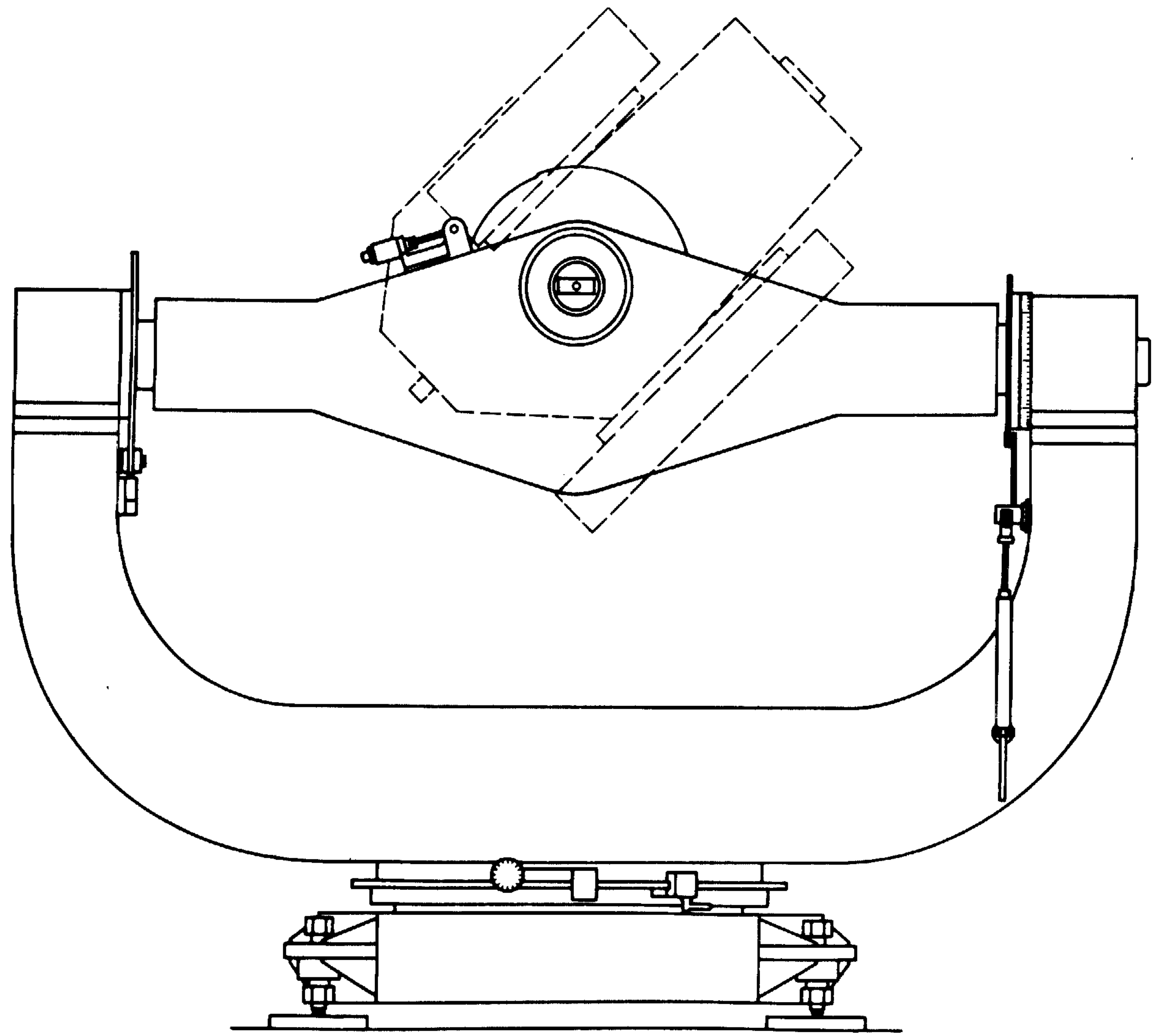


FIGURE 14

RADOT MOUNT



APPENDIX

S-66 OPTICAL MASER SATELLITE TRACKING EXPERIMENT DATA SHEET

SATELLITE NAME :

Polar Ionosphere Beacon Satellite

PRIMARY PURPOSE :

To determine the integrated electron density of the atmosphere over the radiation path, by measuring the phases of a number of harmonically related signals of different frequencies, radiated from the spacecraft, as received at about 60 observing stations throughout the world.

SATELLITE SHAPE (Without reflection):

Octagonal perpendicular prism. Octagonal face diameter, approximately 46 cm. Height (distance between oct gonal faces), approx 28 cm.

WEIGHT :

Total approx 52 kilograms.

POWER SOURCE :

Solar cells on four rectangular paddles, each approx 20 cm by1 meter.

RADIATED FREQUENCIES :

20, 40, 41, 136, 162, 324, 360 Mc/s.

INTENDED ORBIT :

Altitude, 1000 km. Eccentricity, 0 (circular). Inclination 80°. Plane of orbit initially near normal to the line connecting the centers of the earth and sun.

ATTITUDE CONTROL :

Magnetic. One end of the symmetry axis will be directed in the north magnetic direction of the earth's magnetic field. Only this end is suitable for an optical reflector for use in the northern hemisphere. Angle between line of sight and symmetry axis will vary with position. Sl ow rotation about symmetry axis.

./.. .

REFLECTOR SHAPE :

Truncated regular octagonal pyramid.
Octagonal base, approximately 46 cm diameter.
Octagonal top, approximately 19 cm diameter. Perpendicular Height, approximately 22 cm. Covered with a close - packed mosaic of retro - reflecting prisms. Weight of reflector assembly, approx 4, 5 kg.

NUMBER OF CUBE-CORNERS :

360 total. 40 prisms on each of the eight sloping trapezoïdal panels and 40 prisms on the small octagonal face pointing in the magnetic north direction.

DESCRIPTION OF INDIVIDUAL RETRO-REFLECTORS :

Cube-corner prisms, with face through which light enters and leaves cut into the shape of a regular hexagon, approx. 2, 5 cm across flats. Optical specifications are that 80 % of the light falling normal onto the hexagonal face shall be reflected back in the incident direction within a divergence cone having an angular diameter of 10^{-4} radians.

MATERIALS :

Cube corner prisms of radiation-resistant fuzed quartz. Aluminized reflecting surfaces.

TYPICAL CALCULATION :

$$N = \frac{16 E \lambda \Delta^2 \alpha A_s A_R}{\pi^2 h c \theta_t^2 \theta_s^2 R^4}$$

Where
- N = Number of photons per pulse entering a receiver telescope (3.62×10^4 photons)
- E = total pulse energy (1 joule)
- λ = Ruby laser wavelength (6943 A)
- Δ = One-way atmosphere transmission (0, 8)
- A_s = Reflector projected area (200 cm2)
- A_r = Receiving telescope aperture area (500 cm2)
- θ_t = Transmitted beam divergence angular diameter (10^{-3} radian)
- θ_s = Reflector beam divergence (10^{-4} radian)
- R = Range (1500 km).

The numbers in parentheses are intended to be typical conservative parameters as a guide to practical application of S-66.